

Effect of Natural Plant Extracts on Arsenic Toxicity in Aquatic Systems

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ABSTRACT

Arsenic contamination in aquatic system has emerged as an environmental and public health concert because of its toxicological impact on aquatic life and bioaccumulations by the help of aquatic food chain. Conventional methods for arsenic remediation such as coagulation and filtration are often very expensive and environmentally destructive. This encourages the use of plant-based and eco-friendly methods which are cost-effective and at the same time environmentally friendly and has therefore become a very viable option to treat arsenic in water. This review explores the potential of natural plant extracts and their phytochemicals- such as flavonoids, saponins, and alkaloids- in mitigating arsenic toxicity. Bioaccumulation, rhizofiltration, chelation, and antioxidant defense are different mechanisms that are responsible for phytoremediation. A lot of attention is given to the efficiency of different plants like *Azadirachta indica* (also known as a neem tree), *Silybum marianum* (or milk thistle), and *Taraxacum officinale* (a dandelion), as well as water plants such as *Eichhornia crassipes* and *Lemna minor*. These plants have demonstrated the significant potential in absorbing arsenic, reducing oxidative stress and altering arsenic bioavailability in water bodies. Despite its optimistic results, there are still crucial concerns about scaling-up, lasting consistency, and involved molecular pathways in the phytoremediation process that have not been cleared. This review highlights the need for future research to develop optimized plant based strategies for sustainable arsenic detoxification in aquatic environments.

Keywords: Antioxidants, Arsenic Toxicity, Phytochemicals, Phytoremediation, Water Pollution

INTRODUCTION

Arsenic toxicity or arsenic poisoning occurs when someone comes to contact with high levels of arsenic. It is an element (natural) that can be found anywhere, in food, water, or soil. People can be exposed to arsenic due to contaminated water or at workplace. It may cause vomiting, abdominal pain, diarrhoea etc. The hazards of arsenic contamination are similar to the ecosystems present in water. The source of arsenic accumulation in the aquatic bodies can be different. Arsenic may come into aquatic systems through natural sources like weathering of rocks, volcanic outbreaks, and other geothermal activities. Else anthropogenic sources such as human originated mining, industrial effluents, arsenic from pesticides, and improper discarding of arsenic-contaminated waters.

Aquatic environments can be considerably impacted by the presence of heavy metals, such as arsenic, that pose a major threat to aquatic ecosystem and human health (Zhao et al., 2016) (Wasserman et al., 2004). Arsenic contamination in aquatic systems is a pivotal environmental concern worldwide (Mohan and Pittman, 2007). Arsenic is basically a metalloid that can mount up in water ecosystems due to mining, geologic deposits, or industrial activities. Lengthy exposure to arsenic-contaminated water can lead to several health issues, like various types of cancer (Verduzco-Navarro et al., 2022). Particularly, bioaccumulation of arsenic in water bodies can lead to various health diseases like liver damage, poisoning of gills, decreased fertility, tissue damage, and cell death in fish. It also causes changes in behaviour of aquatic creatures, disturbing the survival and reproduction.

Currently available arsenic removal techniques like coagulation, adsorption, and membrane filtration are less effective in remediating waters polluted with arsenic (Verduzco-Navarro et al., 2022). Thus, there is a pressing need to discover alternate approaches, comprising the use of plant-derived extracts from natural origin, to alleviate arsenic toxicity in aquatic ecosystems.

Abundant studies have examined the prospective of natural plant extracts to eradicate and/or reduce the bioavailability of arsenic in water (Langsch et al., 2012). For example, chitosan, a biopolymer found in the exoskeletons of crustaceans, has proved to have arsenic adsorption capabilities. Likewise, alginate, a polysaccharide derived from brown seaweed, was used to encapsulate iron nanoparticles for the elimination of arsenic from aqueous bodies (Ruiz-Mora et al., 2022).

Apart from adsorption, plant-derived materials might also have the capacity to lessen the toxic effects of arsenic on aquatic creatures. For instance, few plant extracts have shown to augment the expression of antioxidant enzymes and reduce oxidative stress caused due to arsenic exposure in fish and varied aquatic life (Langsch et al., 2012).

Natural Plant Extracts: Background

Conventional treatment methods intended at removing contaminants can be difficult economically and environmentally. Subsequently, phytoremediation, the use of plants to eradicate environmental pollutants, has arisen as a cost-effective and green substitute (Garai et al., 2021). Plant extracts have been useful in eradicating unwanted substances from environment especially water bodies (Shankar, Shanker and Shikha, 2014). Phytoremediation is a developing, cost-effective, and eco-friendly way to manage arsenic contamination in aquatic systems. With cumulative industrial activities and inappropriate waste clearance, arsenic pollution has become a dangerous environmental and public health issue. This review appraises the present-day study on phytoremediation strategies to alleviate arsenic toxicity in aquatic systems (Agency for Toxic Substances and Disease Registry (US), 2007).

Aquatic macrophytes, a varied group of plants, have huge potential for the exclusion and degradation of an array of pollutants, including heavy metals (Garai et al., 2021). Aquatic plants like *Azolla filiculoides*, *Ceratophyllum demersum*, *Eichhornia crassipes*, and *Lemna minor* have demonstrated high efficiency in removing arsenic from polluted water (Rahman and Hasegawa, 2011). Particularly, the fern species of the *Pteris* genus are arsenic hyperaccumulator grown in hydroponic system. Moreover, *Pistia stratiotes* (floating macrophytes) have also been known to remove heavy metal from industrial effluents (Rahman and Hasegawa, 2011).

Mechanisms of Phytoremediation:

Aquatic macrophytes remediate arsenic-polluted waters via mechanism of bioaccumulation, biosorption, and rhizofiltration (Rahman and Hasegawa, 2011). Nevertheless, biomass disposal and seasonal growth patterns of plants are grave challenges that need to be addressed to enable the transfer of phytoremediation technologies from the lab to the field (Byeon et al., 2021).

The major detoxification pathways by which the plant extracts affect arsenic's bioavailability, uptake, and toxicity are different.

Bioaccumulation is the process by which substances, like toxins or pollutants, accumulate in the tissues of plants over time. The accumulation is due to the absorption of arsenic faster than it is excreted or metabolized. Bioaccumulation can be sometimes also referred as phytoaccumulation or phytostabilization. Some aquatic plants such as duckweed (*Lemna minor*) and water hyacinth (*Eichhornia crassipes*) have the potential to accumulate arsenic in their biomass thus reducing its bioavailability in water (Rahman and Hasegawa, 2011).

Rhizofiltration is a bioremediation method which uses plant roots to eradicate, concentrate, and/or degrade pollutants from water. This technique leverages the natural ability of plants to absorb and process contaminants via root systems. It's predominantly beneficial for treating water polluted with arsenic. The mechanism of action for rhizofiltration is either absorption where plants take up arsenic with their roots and transport to other parts of the plant. This transport may be passive or active. Secondly, some pollutants may be accumulated and concentrated in the plant tissues and removed from the environment. Additionally, plants can transform or degrade arsenic into less harmful form through native metabolic processes. Specially, plants like *Phragmites australis* and water lettuce (*Pistia stratiotes*) are known for rhizofiltration (Dushenkov et al., 1995).

Chelation and Complexation is a major contributor for detoxification. Numerous studies show that plant compounds are able to bind to arsenic ions, hence reducing their bioavailability and toxicity (Flora et al., 2007). Flavonoids, tannins, and saponins are known to have chelating properties (Tennstedt et al., 2009). Complexation is a method in which arsenic gets modified to form fewer toxic derivatives, thus decreasing the bioavailability of arsenic in the aquatic organisms. Another way uses the antioxidant activity of plant extracts. This involves the neutralization of oxidative stress induced by arsenic. This happens by scavenging of the free radicals and protecting cellular parts from arsenic-induced damage. The detoxification is also influenced by the enzymes that are responsible for modifying the arsenic compounds to non-toxic or less toxic intermediates, ex. glutathione-S-transferases. Yet another form of reduction in arsenic toxicity is by enhancement of microbial activity (Andres and Bertin, 2016). Few plant extracts have been testified to adopt the growth

of particular bacteria that transform arsenic into less toxic molecules, thus helping bioremediation(Kruger et al., 2013)(Fekih et al., 2018)(Sengupta et al., 2023).

There are also some factors that influence phytoremediation like water chemistry: pH, the organic matter composition and content, and competing ions can suggestivelyaffect arsenic uptake by plants. Understanding these factors is crucial for optimizing phytoremediation strategies.

Debates and Challenges

Although plants absorb arsenic there are many issues, controversies around its working. One of the debatable aspects is that of bioavailability and toxicity. The issue is that concern over the impact of accumulation of transformed arsenic into organic form in the plant tissues that might continue the toxicity in the food chain. An alternative way is to generate geneticallymodified organisms to enhance phytoremediation. This raises the issues of ethics and ecological problems(Rascio and Navari-Izzo, 2011). Further, studies are done to assess the short-term effects and applications of phytoremediation, although sustainability and long-term studies are lacking and need comprehensive evaluation. Another facetof challenge is the scaling-up. The transition from laboratory to field still remains a critical task. And field trials are important and essential to resolve scalability matters.

Phytochemical Properties:

Plants consist of an array of primary and secondary metabolites. Some of the major secondary metabolites are flavonoids, saponins, alkaloids. These are believed to influence arsenic toxicity. Studying the mode of action of naturally occurring phytochemicalsto modulate arsenic toxicity is of key interest. The phytochemical compounds interact with arsenic in different ways.

- Flavonoids:** Flavonoids that are polyphenolic phytochemicalspresent in fruits and vegetables have antioxidant properties. Thus, they can alleviate oxidative stress caused by arsenic exposure. Studies show that flavonoids like quercetin can decreasethe oxidative damage caused by arsenic in liver cells(Baltaci et al., 2016). While some authors argue that the effectiveness of flavonoids can vary pointedlydependent on thebioavailability and stability.This highlights the gap in improving flavonoid-rich diets for arsenic toxicity reduction.
- Saponins:** Saponins are basically glycosidic compounds usually found in legumes and few herbs. They have detoxifying properties that bind to heavy metals, including arsenic, and enable their excretion (Mariana et al., 2017; Akaninyene, 2022). Though, there is a constant debate regarding the optimum concentration and possible side effects of saponins in long-term contact. Studies also havepecified mixed results about saponins' role in chronic arsenic poisoning, recommending the need for further detailed toxicological assessments.
- Alkaloids:** Alkaloids are a varied group of naturalcompounds with substantial pharmacological activities. Research demonstrated that certain alkaloids can inhibit apoptosis induced by arsenic in kidney cells(Mariana et al., 2017). Contrarywise, fewunderline the fact that some alkaloids might interfere with arsenic metabolism, possiblyaggravating its toxicity. This opposing evidence displays a gap in understanding the dual nature of alkaloids' interaction with arsenic, requiring more in-depth research.

Table 1: Describes The Plant-Derived Phytochemicals, Its Mechanism Of Action And Their Potential Arsenic Detoxifying Effect

Phytochemical	Plant Source	Class of Compound	Mechanism of Action	Effect on Arsenic Toxicity	Reference
Curcumin	Curcuma longa (Turmeric)	Polyphenol	Antioxidant, chelates arsenic, decreases oxidative stress	Drops ROS, reduces lipid peroxidation, protects DNA	(Adil et al., 2015)
Quercetin	Onions, apples, tea, capers	Flavonoid	Hunts free radicals, inhibits arsenic-induced apoptosis	Shields cells from oxidative damage and genotoxicity	(Adusei and Azupio, 2022)
Resveratrol	Grapes, berries	Stilbene	Antioxidant, activates detoxification enzymes (SOD, CAT)	Lessens arsenic-induced oxidative stress and inflammation	(Adil et al., 2015; Sabitha et al., 2021)
Epigallocatechin	Green tea	Flavonoid	Antioxidant,	Declines	(Sinha, Roy and

gallate (EGCG)	(Camellia sinensis)		prevents DNA damage and apoptosis	oxidative damage and inflammation	Roy, 2010)(Guvvala et al., 2017)
Silymarin	Milk thistle (Silybum marianum)	Flavonolignan	Guards against oxidative stress, enhances GSH levels	Guards' liver cells from arsenic toxicity	(Akaninyene, 2022)
Luteolin	Celery, parsley, artichokes	Flavonoid	Antioxidant, anti-inflammatory, inhibits cell apoptosis	Decreases ROS and improves cell survival	(Jayawickreme et al., 2024)
Ginsenosides	Ginseng (Panax ginseng)	Saponin	Stimulates antioxidant enzymes, reduces oxidative damage	Mitigates arsenic-induced stress responses	(Akaninyene, 2022) (Jayakodi et al., 2018)
Rutin	Buckwheat, citrus fruits	Flavonoid	Antioxidant, metal chelation	Lowers arsenic accumulation, enhances antioxidant response	(Sabitha et al., 2021)
Allicin	Garlic (Allium sativum)	Organosulfur compound	Improves detoxification, increases GSH and metal-binding proteins	Reduces arsenic-induced oxidative stress and DNA damage	(Tennstedt et al., 2009) (Akter, Neelotpol and Kabir, 2022)
Naringin	Grapefruit, citrus fruits	Flavonoid	Antioxidant, reduces arsenic-induced ROS	Ameliorates oxidative damage and enhances survival	(Adil et al., 2015)
Phytochelatin	Various plants	Peptides	Bind and sequester arsenic, reducing its toxicity	Chelates arsenic, reducing cellular damage	(Tennstedt et al., 2009)
Catechin	Tea, cacao	Flavonoid	Forages free radicals, enhances antioxidant defenses	Decreases oxidative stress and cellular damage	(Sinha, Roy and Roy, 2010)

Gaps in literature

We are aware of different mechanisms by which phytochemicals can mitigate arsenic stress, but there is no clear evidence of the exact mode of action. There are many debates around this point. A prominent issue is the antioxidant capacity of phytochemicals in responding to oxidative stress induced by arsenic. This is only possible if there are strong reports and studies about the bioavailability and metabolic influences of these compounds. The metabolic fate of phytochemicals can influence the effectiveness to a great extent. A substantial gap in terms of extensive clinical trials and optimization in dosage and delivery of phytochemical interventions. Also, the multifaceted levels of interaction and effect between diverse phytochemicals and their combinations need to be more explored to augment therapeutic strategies.

Critics argue that more detailed assessments of environmental impacts are needed.

- 1) Long-term issues and Stability: There is a scarcity of longitudinal reports on the long-term stability and efficiency of plant-based remedies in dynamic aquatic environments. Most studies focus on short-term outcomes and lack proof of benefits and possible cumulative ecological side-effects.

- 2) Understanding Molecular Mechanisms: Detailed molecular studies on how precisemolecules within plant extracts associate and interact and affect arsenic are very less. This demonstrates an important gap in connecting phytochemistry with ecological and toxicological consequences.
- 3) Scalability and Economic Feasibility: Although the use of plant extracts is promising in controlled settings, scalability in large bodies of water is a challenge. Exclusive studies assessing the economic costs against conventional ways are required to support wider application. The efficacy of plant extracts can vary depending on the method of application as well. Bioreactors with plant extracts offer controlled conditions for optimal activity, while direct application is easier although less predictable (Shankar, Shanker and Shikha, 2014).

Effectiveness of Different Plant Extracts

Many plants are known to have phytoremediation properties particularly for arsenic toxicity. Here we will in detail discuss the effect of few known plants and the challenges and gaps of knowledge related to them.

Neem (*Azadirachta indica*):

Neem has garnered attention in the aspect of reducing arsenic toxicity because of its distinct phytochemical profile and likely therapeutic properties. Neem is rich in bioactive molecules such as quercetin, azadirachtin, and nimbodin, that have been studied for their pharmacological action. The formation and characterization of silver nanoparticles from neem show to have antibacterial properties. This may also extend to detoxify various toxins, like arsenic (Mariana et al., 2017; Gautam, Pandey and Dubey, 2020).

Recent reports indicate that Neem extracts can assuage arsenic toxicity in plants by dropping arsenic uptake and improving the antioxidant system. For example, study on rice seedlings treated with neem demonstrated a significant reduction in arsenic buildup and an improved plants' antioxidant responses (Nwobodo et al., 2018). These results suggest that the antioxidant properties of neem phytochemicals might have a crucial role in modifying the oxidative stress damage caused by arsenic exposure.

Numerous studies have examined the comparative effectiveness of neem against other botanical extracts in modifying insecticidal effects and antimicrobial properties. Also, the preparation of Neem oil nanoemulsions has shown effect against pests, additionally supporting the fact that neem formulations can augment its efficacy in many applications, also including arsenic detoxification (Garai et al., 2021).

Despite the promising evidence of Neem's effect in reducing arsenic toxicity, many gaps remain in the existing literature. Primarily, there is a major focus on the antioxidant properties of Neem, but there is less understanding of the particular phytochemicals responsible for the effects against arsenic. Moreover, most experiments have been performed in vitro or in plant models and lack comprehensive in vivo studies in mammals which can further validate findings. Further, how neem phytochemicals interact with arsenic at the molecular level are still not known. Comprehension of these mechanisms is critical for development of targeted therapies and applied application in mitigating arsenic toxicity (Ahammad et al., 2021).

In order to address these shortcomings, future research must focus on the following aspects:

Isolation and Classification of Phytochemicals: Comprehensive studies on isolating particular phytochemical from neem and evaluating their individual and synergistic effect on arsenic toxicity are vital.

Mechanistic Studies: Inspecting the molecular mechanisms and pathways involved in the detoxification process carried out by Neem phytochemicals can reveal novel therapeutic targets for arsenic poisoning.

Formulation Development: Assessing the development of Neem-based formulation or delivery methods to improve the bioavailability and effectiveness against arsenic toxicity in various environments.

In Vivo Studies: Performing animal studies to evaluate the shielding effects of Neem against arsenic shall provide more robust indication of its usefulness.

Broader Toxicological Assessments: Increasing the scope of research to involve the evaluation of effect of neem on other heavy metals and toxins shall aid establish its versatility as a detoxifying agent.

Thus, neem presents a promising avenue for investigation into natural remedy for arsenic toxicity. With its rich phytochemical content and verified efficacy in reducing toxin levels, additional studies into its mechanisms and applications are warranted. Talking about knowledge gaps, targeted research shall enhance our understanding of Neem's ability but can also contribute to emerging active strategies for fighting arsenic and other environmental toxins.

Milk Thistle (*Silybum marianum*): Milk thistle is one of the plants that has attracted

attention due to its antioxidant properties and ability to protect against cellular damage. The major compound reported to be active for this property is silymarin, a flavonoid complex (Heidarian and Nouri, 2021). Silymarin exhibits protective effects against various toxins, counting heavy metals and organic pollutants. Author have published a complete review elaborating the clinical properties of silymarin, emphasizing its antioxidant and hepatoprotective effects. These results suggest that silymarin might also offer protective role against arsenic-induced damage in aquatic fauna. Research into these areas of effects of silymarin on aquatic organisms exposed to arsenic is still in its infancy. But, the probability of silymarin to lessen arsenic toxicity is promising due to the antioxidant defenses and reduction in oxidative stress in mammalian systems (Heidarian and Nouri, 2021).

Despite the encouraging findings of silymarin's protective properties, many knowledge gaps remain related to its application to aquatic organisms. Firstly, there is a lack of direct knowledge assessing the effectiveness of silymarin in reducing arsenic damage in aquatic environments. Also, the precise mechanisms by which silymarin exerts its defensive effects in aquatics are not known. Future studies should aim to clarify these mechanisms, chiefly focusing on the role of oxidative stress variation and cellular signaling pathways. Additionally, research should also be carried out to investigate the optimal dosages and exposure durations of silymarin to regulate its efficacy in real-world aquatic systems. In all, silymarin from Milk Thistle is a potentially valuable asset for protecting aquatic systems from arsenic damage.

Dandelion (*Taraxacum Officinale*):

While widespread research has been directed on contamination of heavy metal and its effect on plants and aquatic organisms (Lu et al., 2021; Kurbonalijon et al., 2024), the role of Dandelion in arsenic bioavailability is underexplored. Dandelion has established a potential in phytoremediation. Microbial communities play an important role in the biotransformation and mobilization of arsenic in aquatic environments. The association of Dandelion and microbial populations in contaminated aquatic systems might influence the availability of arsenic. The comprehension of these dynamics could disclose new approaches to improve phytoremediation approaches, possibly leading to healthier aquatic ecosystems (Posthuma et al., 2019).

In spite of the crucial implications of Dandelion in reducing arsenic toxicity, much needs to be known (Lu et al., 2021):

- a) Exact mechanism of action: The biochemical pathways through which Dandelion affects arsenic uptake and detoxification are required to be more explored. Studies also need to focus to understand the metabolic responses of Dandelion to arsenic exposure and its implications towards aquatic organisms (Kurbanalijon et al., 2024).
- b) Ecotoxicological Assessments: More extensive ecotoxicological studies need to be assessed to verify the impact of Dandelion on aquatic creatures exposed to arsenic. These experiments should not only examine survival rate but also effects on growth, reproduction, and behaviour.
- c) Plant-Microbe Interactions: There is less information on how Dandelion interacts with microbes in arsenic-contaminated waters. Studies could examine the synergistic effects of Dandelion and particular microbe species on arsenic toxicity.
- d) Long-term Effects: The long-term effect of Dandelion phytoremediation on aquatic health and dynamics are not understood. Longitudinal studies can provide visions into the sustainability of Dandelion for arsenic remediation.
- e) Others: For instance, the application of plant extracts from *Azolla filiculoides* has been shown to significantly accumulate arsenic in concentrations up to 30 μM , showcasing its effectiveness under challenging conditions such as low pH.

EXPERIMENTAL APPROACHES AND FINDINGS

Laboratory Studies:

- In vitro and controlled environment experiments have highlighted the mechanisms by which plant extracts can lessen arsenic toxicity. The studies have exposed that dissimilar plant species employ diverse approaches to uptake, transport, and detoxify arsenic. For example, some plants can reduce arsenate to less toxic arsenite, while others apply antioxidant mechanism and thiol-based complexes to manage oxidative stress induced by arsenic.
- The review published by Srivastava and Dubey delivers a complete overview of the biochemical and underlying molecular mechanisms of arsenic toxicity, accretion, and detoxification in plants. The authors emphasize the potential of genetic modifications to enhance arsenic tolerance and decrease food chain contamination. Likewise, an article researches into the effect of glutathione S-transferases in contending stress, including arsenic detoxification in plants.

Table 2: Summary of various analytical, bioassay, and molecular techniques used to study arsenic toxicity in aquatic environments, focusing on arsenic detection, its biological impacts, and related biochemical responses

Technique	Purpose	Systems Studied	Measured Parameters	Outcomes	Reference
Atomic Absorption Spectroscopy (AAS)	Measure arsenic concentration in water samples	Aquatic ecosystems (e.g., rivers, lakes)	Arsenic absorption in water and sediments	Discovery of varying arsenic levels in water bodies	(Bhat et al., 2022)
Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	Trace metal analysis, including arsenic in water systems	Sediments, water samples from contaminated sites	Total arsenic concentration, speciation of as(III) and as(V)	Variation of arsenic species and assessment of their toxicity levels	(Bhat et al., 2022)
Bioassay with Fish (Zebrafish)	Assess biological effects of arsenic exposure	Zebrafish embryos and adult fish	Mortality rate, morphological abnormalities, behavior changes	Amplified mortality and developmental defects at higher arsenic concentrations	(Pérez Coll et al., 2018)
Microtox Assay	Evaluate arsenic toxicity using bacterial bioluminescence	Marine and freshwater bacteria	Bioluminescence inhibition	Inhibition of bacterial light emission with cumulative arsenic concentration	(Rabbane et al., 2022)
Comet Assay (Single-cell gel electrophoresis)	Detect DNA damage in aquatic organisms	Fish gill cells, mollusk hemocytes	DNA strand breaks (comet tail length and moment)	Substantial DNA damage in aquatic organisms exposed to arsenic	(Hallauer et al., 2016; Rabbane et al., 2022)
Histopathology of Fish Gills and Liver	Assess tissue damage due to arsenic exposure	Fish (Tilapia, Zebrafish)	Gills and liver tissue structure, necrosis, lesions	Severe tissue damage in gills and liver of arsenic-exposed fish	(Rabbane et al., 2022)
Chlorophyll Fluorescence (PAM Fluorometry)	Measure effects of arsenic on phytoplankton	Phytoplankton communities (algae)	Photosynthetic efficiency (Fv/Fm ratio)	Decrease in photosynthetic efficiency in arsenic-exposed phytoplankton	(Bhat et al., 2022)
Enzyme Activity Assays	Evaluate biochemical responses to arsenic exposure	Fish (Rainbow trout, catfish)	Activity of antioxidant enzymes (SOD, CAT, GPx)	Altered enzyme activities indicating oxidative stress from arsenic exposure	(Hallauer et al., 2016)
Algal Bioassays (Growth inhibition tests)	Assess the impact of arsenic on algal growth	Green algae (Chlorella, Scenedesmus)	Growth rate, cell density	Important inhibition of algal growth with increasing arsenic concentrations	(Rabbane et al., 2022)
Electrochemical Analysis (Anodic Stripping Voltammetry)	Detect arsenic in water samples	Freshwater, marine water samples	Arsenic concentration	Highly sensitive detection of arsenic, even at trace levels	(Bhat et al., 2022) (Rajkumar, Thiagarajan and Chen, 2011)
Real-time PCR (qPCR)	Assess gene expression changes due to arsenic exposure	Fish, amphibians, aquatic invertebrates	Expression levels of stress-related genes (e.g., HSP, MT)	Altered expression of stress and detoxification-related genes in arsenic-exposed organisms	(Bhat et al., 2022)
LC-MS/MS (Liquid Chromatography-Mass Spectrometry)	Arsenic metabolite detection in aquatic organisms	Fish tissues, aquatic plants	Arsenic metabolite profile	Identification of arsenic metabolites and detoxification products in aquatic organisms	(Bhat et al., 2022)

Field Studies: A review of real-world utility and observations regarding the effect of plant extracts on arsenic toxicity in aquatic systems reveals many key findings:

- a. **Phytoremediation:** Many long-term field studies have confirmed the likelihood of aquatic plants like water hyacinth and duckweed in eliminating arsenic from water bodies. - These plants accumulate arsenic in tissues, successfully dropping arsenic concentrations in water (Kurbanalijon et al., 2024).
- b. **Large-scale treatments:** Constructed wetlands that use specific plant species show promising data in arsenic removal from water. Long-term observation of these systems provide valuable information on the sustainability and competence of plant-based arsenic remediation (Rahman and Hasegawa, 2011; Lu et al., 2021).
- c. **Biochar applications:** Studies suggested that plant-derived biochar can be used as a soil amendment and have potential in dipping arsenic mobility and bioavailability in aquatic sediments. Long-term field studies have shown the consistency of biochar's arsenic-binding effects over many years (Ruiz-Mora et al., 2022).
- d. **Mitigation by algal bloom:** Studies on using plant extracts to regulate algal blooms in arsenic-contaminated waters showed the potential in dropping arsenic toxicity and eutrophication. Multi-year experiments in eutrophic lakes provided data into the long-term effects of this method (Gensemer et al., 2018).
- e. **Aquaculture applications:** Survey on using plant extracts as feed additives in aquaculture systems exposed to arsenic demonstrated positive results in dipping arsenic in fish tissues.

While these real-world use cases and reports display the benefits of plant extracts in vindicating arsenic toxicity in aquatic systems, more widespread and longer-term experiments need to be done to fully comprehend their usefulness and sustainability.

Bioassays and Indicators:

In the process of arsenic phytoremediation, evaluating the efficacy of plants and extracts includes a range of methods to assess plant growth, arsenic uptake, toxicity mitigation, and biochemical responses (Pérez Coll et al., 2018).

Growth Assays:

Growth assays are important in finding how arsenic contamination and phytoremediation treatments affect plant health and development. These include biomass measurement particularly, fresh, and dry weight, root and shoot length, leaf area, and chlorophyll content:

Survival Rates:

In arsenic toxicity tests, the survival of plants is a straight indicator of toxicity. A higher survival rate in phytoremediation-treated indicates the protective effects of treatment.

Arsenic Concentration:

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is one of the sensitive practices to quantify arsenic concentrations in plant tissues. It senses trace amounts of arsenic and offers perceptions into how much arsenic plant is capturing. Tissue Distribution is used to identify the distribution of arsenic in different parts of the plant (root vs. shoot), that helps in understanding arsenic transport and accumulation. X-ray Fluorescence (XRF) is a non-destructive technique used to map presence of arsenic in plant tissues, giving visual picture of how arsenic moves in the plant.

Biochemical Markers of Stress and Detoxification provide insight into how arsenic changes plant metabolism and how phytoremediation counteract these effects (Hook, Gallagher and Batley, 2014).

Reactive Oxygen Species (ROS) Levels are measured using fluorescent probes like DCFH-DA, which emit fluorescence according to ROS levels. A decrease in ROS levels post phytoremediation treatment indicates and reduced oxidative damage. Similarly, lipid Peroxidation (MDA Content) is a marker of oxidative stress caused by arsenic toxicity. Further, enzymes like Superoxide Dismutase (SOD), Catalase (CAT), Glutathione Reductase (GR) and Peroxidase (POD), Glutathione (GSH) are calculated to find how well plants are dealing arsenic-induced oxidative stress.

Applications and Future Directions

Studies must be done to explore novel plant species that have the potential to detoxify arsenic. There is lot of scope to study the effect of Large-Scale Use of phytoremediation into practical implications. There are research Gaps in identification of long-term effects, optimization, economic viability, and of extract formulations (Belanger et al., 2017). Further, innovative Approaches such as genetically modified plants or novel extraction methods, which could enhance effectiveness can be developed.

CONCLUSION

Research on the use of plant extracts in vindicating arsenic toxicity in aquatic ecosystems has shown considerable potential but is yet in its nascent stages. While promising actions and applications have been recognized, debates concerning efficacy, ecological influence, and practical execution remain. Addressing gaps, specifically concerning long-term impressions and scalability, is key to advancing this field. Additionally, interdisciplinary research is essential to harness the full probability of plant-based solutions for arsenic in aquatic ecosystems.

This review underlines the crucial role of specific phytochemical complexes in moderating arsenic toxicity. Flavonoids, saponins, and alkaloids are promising but considerable studies are essential to establish conclusive protective mechanisms. Discussing the highlighted gaps, like bioavailability and compound associations, can meaningfully enhance the use of phytochemicals in handling arsenic exposure risks.

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